INVESTIGATION OF TOOL WEAR AND SURFACE FINISH BY ANALYZING VIBRATION SIGNALS IN TURNING *ASSAB-705* STEEL

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□ *Various occurrences in machining influence the machining dynamics and thus produce vibration in the cutting tool-workpiece arrangement. In this investigation, with tri-axial accelerometer mounted on the tool-holder in turning* ASSAB-705 *steel, vibration signals have been captured with and without cutting. The nature of vibrations arising in the cutting tool at different cutting conditions has been investigated. It has been observed that the RMS amplitude of vibration along all three axes for the increasing cutting speed was mixed in nature; however, an increasing trend was noticed in the vibrations along the feed,* V_x *and radial,* V_y *directions. The vibration along the main cutting direction,* V_z *was mixed, initiated by large vibration and then decreased until a particular cutting speed was reached and finally increased steadily. The feed vibration component,* V_x *has a similar response to the change of the workpiece surface roughness, while the other two components,* V_y *and* V_z *have the more coherent response to the rate of flank wear progression throughout the tool life. The natural frequency of different machine parts vibration has been found to be within the band of 0 Hz – 4.2 kHz, whereas the frequencies of different occurrences in turning varied between 98 Hz and 42 kHz.*

Keywords chip formation, frequency analysis, surface roughness, tool wear, vibration

INTRODUCTION

The fluctuation of dynamic force components from different source or sources within the system of a machining process generates vibration into different machine tools and affects the cutting process dynamics. In metal cutting, three different types of mechanical vibrations such as free, force and self-excited vibration arise due to the lack of dynamic stiffness of one or several elements of the system. Free vibrations occur as a result of collision between the cutting tool and the workpiece when an incorrect tool path is

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defined. Forced vibrations primarily occur during engagement, and disengagement, of the cutting tool with, and from, the workpiece, respectively.

The unbalanced bearings or cutting tools also induce the system with forced vibration. The effect of these free and forced vibrations on cutting tool can be avoided, reduced or eliminated when the causes of the vibration are identified and being monitored during machining (Quintana and Ciurana, 2011). Some other sources of vibration, on the other hand, are unavoidable, such as the release of residual stress formation in the machined surface producing vibration in the tool-workpiece arrangement. Micro-cracking and tearing-out of material also cause vibration in the machining process, which is the principle of tool wear mechanism (Desforges et al., 2011). The level of vibration is largely determined by the cutting conditions like cutting speed, feed rate and depth of cut, tool wear, and workpiece inclination angle (Li et al., 2013).

The feed rate and depth of cut are recognized to be the dominant factors for the vibration amplitude (Ghani et al., 2002). At a low spindle speed, no chatter usually occurs and vibration amplitude is dampened, whereas it diminishes at a high spindle speed (Quintana and Ciurana, 2011). Tabatabaei et al. (2013) have investigated the high chip removal as to be the cause of regenerative chatter vibration. The vibration amplitude, on the other hand, exhibits a negative relationship with radial rake angle and nose radius. No significant change in the amplitude of vibration appears with the varying tool rotational speed and different work material (Kumar, 2013).

Tool condition monitoring using vibration measurement would be rather reliable than some conventional methods, which are usually biased and incomplete due to their limited concern to some particular occurrence or frequency. For example, the commonly used Taylor tool life model is deterministic in nature, but uncertainty exists due to the factors that are unknown or not included in the model, and also for tool-to-tool performance variation (Karandikar et al., 2013). Besides, tool wear comprises of flank wear, crater wear/rake wear, notch wear, etc., what makes the measuring process rather difficult to investigate the respective effects according to their types (Niu et al., 2013). Likewise, merely monitoring the surface roughness of workpiece cannot ensure the proper surveillance of cutting process (Isbilir and Ghassemieh, 2013). Monitoring vibration in machining, therefore, could provide more complete information about the cutting tool and cutting process as it includes frequency from entire occurrences that take place during machining.

An effective vibration investigation system would correspond to all occurrences taking places in machining, e.g., tool wear, chipping, tool fracture, tool breakage, chip formation, collision between tool, chip and workpiece, chip tangling, interruption between tool and workpiece contact, workpiece surface finish and process stability and so on. The application of vibration toring has been observed in different investigations in turning (Kalvoda and Hwang, 2010; Zhu et al., 2013).

During monitoring, the signals captured from the accelerometer are analyzed using wavelet, power spectrum RMS, FFT, TFD and so on to extract the significant features out of them (Kalvoda and Hwang, 2010; Loutas et al., 2011). The RMS of the raw signal represents the intensity level of vibration at different machine parts that are generated in machining. As the data collected are time domain signal, and digitized before storing, the frequency analysis could easily be performed on to them by converting the time-domain data into the frequency spectra (Abu-Mahfouz, 2003; Ebersbach and Peng, 2008; Loutas et al., 2011; Peng and Chu 2004).

The objective is to obtain a frequency decomposition of the original signal in which the features are best correlated with the occurrences and thus can be detected in a simple fashion (Alonso and Salgado, 2008). In this study, the raw signal, its RMS and frequency analysis have been utilized to evaluate the machine tool vibration recorded under different cutting conditions during machining. The study has been carried out to investigate the effects of different occurrences on cutting tool condition based on the measurement of tool holder vibration in turning. This investigation has also intended to identify the frequencies or band of frequencies of various occurrences responsible for tool damage. The findings of this study would help to develop an indirect monitoring system to identify the cutting tool condition and the different occurrences responsible for damaging the tool state without interrupting the machining process.

MATERIALS AND METHODS

In the turning process, the workpiece and tool-insert are the extreme bodies of the system which are directly involved with the cutting action. However, it is really difficult and unrealistic to mount the sensor on such a tiny tool insert to measure its vibration. On the other hand, the tool-holder is directly involved with the tool-insert which is therefore, effectively induced by the vibration of tool-insert that are produced and transmitted from the process of metal cutting.

Material was cut under variable cutting conditions, and the vibration was measured from the system during the investigation. The different tool condition defining parameters like flank wear and surface roughness were also measured to correlate with the intensity and frequency of the tool vibration to identify the cutting tool condition. To predict the cutting tool condition by measuring the cutting tool vibration, the vibration sensor/accelerometer was located on the tool holder to capture the vibration signals. To make

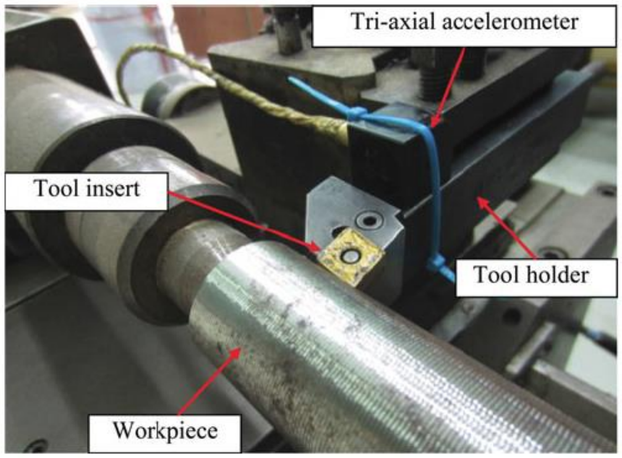

FIGURE 1 Real view of experimental setup.

the investigation effective, the recorded signals are required to be processed to extract the best useful features out of them. The raw vibration signal, its RMS and frequency analysis have been used to illustrate the sensor's output captured from the tool holder during the investigation.

Experimental Setup

A circular workpiece of 9.2 cm diameter and 38 cm long steel rod was mounted on a Colchester VS Master3250 165 mm × 1270 mm gap bed center lathe machine (Heckmondwike, West Yorkshire, UK) with the help of a self-centering type three jawed mandrel in the headstock and a tailstock. A tri-axial accelerometer, Kistler 8762A50 (Toronto, Canada) with the sensitivity of 100 ± 5% mV/g was mounted on the top surface of the tool holder and very close to the insert location. The experimental setup shown in Figure 1 illustrates the location of the accelerometer.

The *x*-, *y*- and *z*-directions of the accelerometer on the tool holder correspond to the feed force, radial force and main cutting force directions respectively during cutting. A sampling rate at 200 kHz was set during the entire experiment. At first, the vibration level of the cutting tool holder has been measured without any cutting at different cutting speeds and feed rates. This was done to observe the amplitude of vibration along *x*-, *y*- and *z*-directions due to the machine vibration only and some other unavoidable sources even if no cutting is conducted. Then the vibration of the tool holder has been recorded during cutting at different cutting speeds, feed rates and depths of cut used for the investigation. The procedure of vibration signal acquisition from the tool holder during the investigation follows the pattern schematically illustrated in Figure 2.

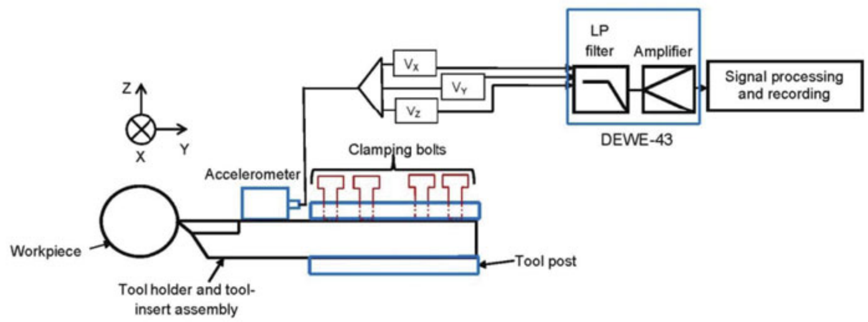

FIGURE 2 The schematic view of experimental setup.

The signals captured from the sensor are passed through a DEWE-43 module (Gabrsko, Trbovlje, Slovenia) before storing for further processing. The DEWE-43 module contains a low-pass filter which permits frequencies below a cut-off frequency of 1000 kHz to pass while blocking the passage of frequency information above the cut-off frequency. The filtered signal is then amplified and digitized before storing for further analysis.

The flank wear of the cutting tool, on the other hand, has been measured by taking the tool insert off from the setup after every run of 2 minutes throughout the tool life. The images of flank wear have been captured by a light source microscope, model I-CAMSCOPE(G) (Toronto, Canada) with a magnification of 40×; the flank wears were then measured from the recorded images using a measuring software called Measure IT. At the same time, the corresponding surface roughness of the workpiece has been measured with a handy profile-meter type: Mahr Perth meter M1/M1 CNOMO 3755350 (Göttingen, Lower Saxony, Germany).

Work Material and Cutting Tool

The workpiece used in the experiment was *ASSAB-705*, a medium carbon steel of hardness HB270-310. By weight, it contains carbon (0.35%), chromium (1.40%), iron (95.95%), manganese (0.70%), molybdenum (0.20%), and nickel (1.40%). The *TiN*-coated carbide, type: SNMG 12 04 08-PM tool insert and DSBNR 2525M 12 tool holder assembly were used as cutting tool arrangement. The experiment has been conducted in dry cutting mode for this investigation. The cutting conditions and tool-workpiece combination have potential effect on tool wear and therefore, on the surface roughness. The mode of experiment was based on varying one-variable at a time while keeping the other two constant.

In this continuous turning operation, velocity was varied from 120 m/min to 270 m/min, while keeping the feed rate constant at 0.32 mm/rev and depth of cut at 1 mm. Similarly, the feed rate was varied from 0.20 mm/rev to 0.50 mm/rev at a constant speed of 250 m/min and

TABLE 1 Cutting Conditions

Cutting speed, v (m/min)	120, 150, 170, 215, 250, 270
Feed rate, f (mm/rev)	0.20, 0.28, 0.32, 0.50
Depth of cut, a_p (mm)	0.5, 1, 2

depth of cut of 1 mm. Also the depth of cut was varied from 0.5 mm to 2 mm at the constant speed of 250 m/min and feed rate of 0.32 mm/rev. For the set of cutting conditions, the spindle speed has varied between 570 rpm and 1283 rpm depending on the cutting speed. Turning and material removal from workpiece was continued until the final diameter of the workpiece became 4.1 cm.

The detail of the cutting condition is presented in Table 1. At each cutting condition, the turning process continued until tool failure, which was based on the average flank wear ($VB = 0.3$ mm). The flank wear has been measured at a time interval of 2 minutes until tool failure, and this was done by removing the tool from the experimental setup. At each of the cutting conditions, vibration signals have been recorded along with the average flank wear and surface roughness of work material. Chips have been also collected at every cutting condition throughout the tool life.

RESULTS AND DISCUSSION

The captured vibration signals were complex in nature as it contained variety of frequencies from different occurrences. The investigation has been performed by developing a correlation between the tool state, cutting conditions and the corresponding vibration level of the tool holder.

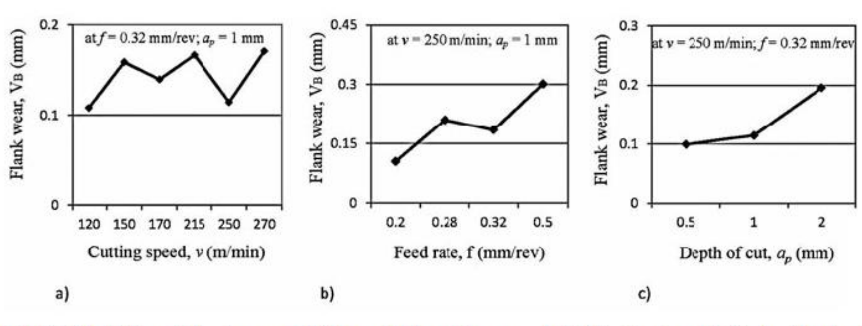

FIGURE 3 Variation of flank wear at different (a) cutting speed, (b) feed rate, and (c) depth of cut in turning.

Tool Wear at Various Cutting Speeds, Feeds and Depths of Cut

Figures 3a to 3c represent the trend of flank wear progression with the change of cutting speed, feed rate and depth of cut, respectively. The cutting time was set at 12 minutes for each cutting speed. The reason for 12 minutes of cutting time was that for each cutting speed, the steady flank wear values were observed in the range of 10–20 minutes.

From the figures, the trend of wear pattern after 12 minutes of cutting time at different speeds and feed rates appears to be mixed. With the increase of speed (Figure 3a), the flank wear increase is not consistent. The flank wear was minimal at 120 m/min cutting speed. At 150 m/min, flank wear increased, and then fluctuated between 170 m/min and 270 m/min. At the highest speed of 270 m/min, flank wear was maximal. The fluctuation could be attributed to the occurrence of strain hardening of work material, which causes an increase in flank wear, plastic deformation and thermal softening of work material, resulting in a decrease of flank wear (Ghani et al., 2002).

At a cutting speed of 170 m/min, the tool wear was observed to slightly drop rather increase with increasing cutting speed. This drop of tool wear can be attributed to the phenomenon of chip formation, when the type of chip formation was found broken into moderate length of pieces (Table 2c). That change apparently had an essential influence on the flank wear resulting in a drop in wear value. At a cutting speed of 215 m/min, the flank wear was found to increase again with the increase of cutting speed. However, at a cutting speed of 250 m/min, the flank wear was exceptionally low even though the cutting speed was higher. That was because of broken chip formation (Table 2e), the stress developed inside the work material was released and minimized the cutting force leading to a low flank wear. At a cutting speed of 270 m/min, the flank wear was observed to be the highest.

From Figure 3b, the flank wear of the cutting tool at a constant cutting speed of 250 m/min and depth of cut of 1 mm were monitored for 12 minutes at different feed rates. At a feed rate of 0.20 mm/rev, the flank wear was observed to be minimum, which then increased with the increase of feed rate at 0.28 mm/rev. With the increase of feed rate, the cutting tool had to travel a longer distance and thus cut more work material that underwent plastic deformation from the workpiece. This incidence essentially increases the cutting force and friction between the workpiece and tool insert, which are damaging to the state of the tool insert and causes an increased flank wear (Ghani et al., 2002).

Nonetheless, an exception was found at a feed rate of 0.32 mm/rev when the tool wear dropped even though the feed rate was higher. This can be attributed to the occurrence of broken chip formation (Table 2e) that caused the release of stress developed, minimized the cutting force and impeded the phenomenon of crack propagation. At the final feed rate of 0.50 mm/rev, this was observed to increase again.

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